Lattice QCD and Experiment,
Revealing the Structure of Hadrons
JLab, 21-22 Nov. 2008

Experimental Study of Generalized Parton Distributions

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GPDs accessed via Deeply Virtual Exclusive Reactions

$ep \rightarrow ep\gamma$

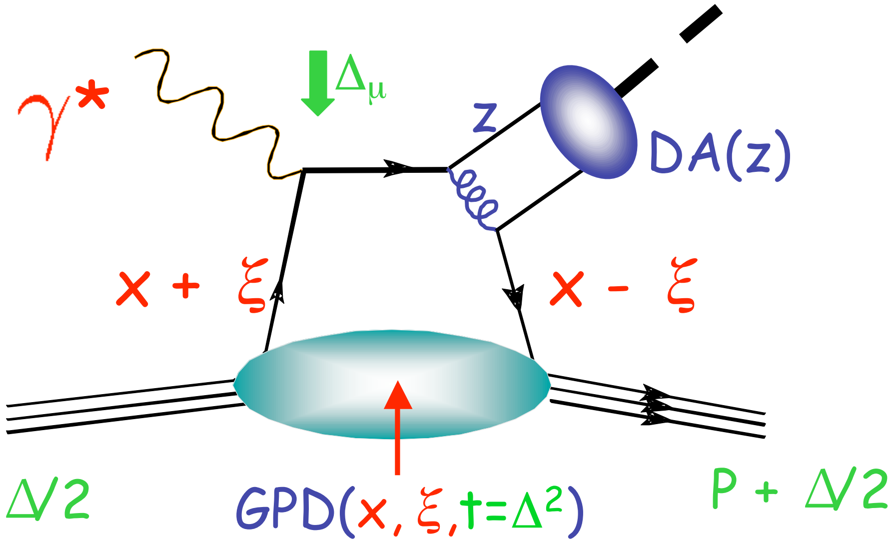
$ep \rightarrow eNm$

Q^2, W^2 large

$-t/Q^2 << 1$

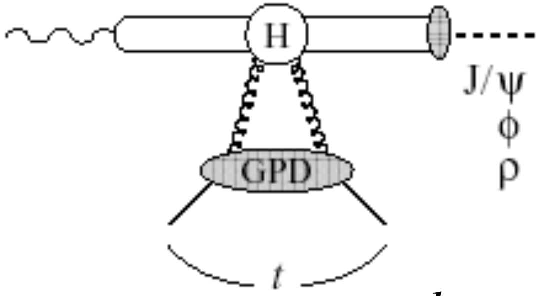
- Experiment must determine Q^2 scale of factorization and/or isolate leading twist terms from Q^2-dependence.

Deeply Virtual Meson Production

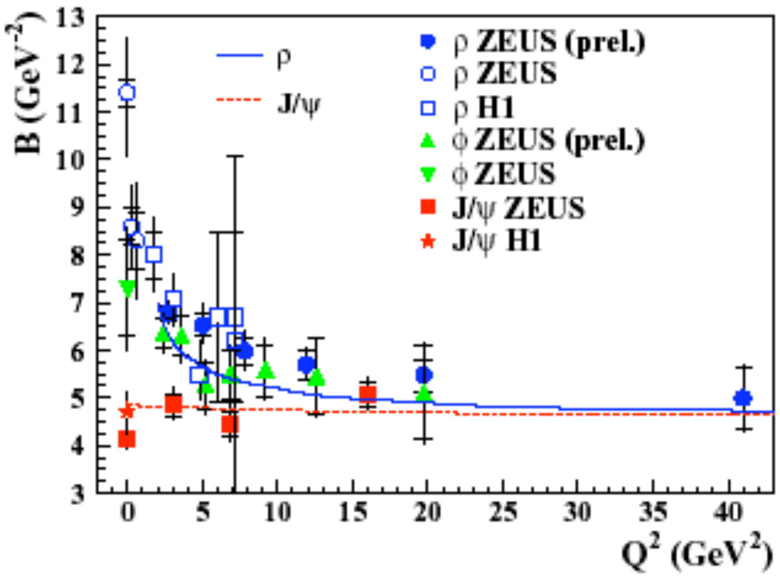


- $\sigma_L \sim [Q^2]^{-3}$
  - $\sigma_T \sim [Q^2]^{-4}$
- ep→e'NV, Vector Mesons
  - H, E
  - Flavor Sensitivity for $\rho^{0,+}$, ω, ϕ.
- ep→e'Nm, Pseudo-scalar mesons
  - ~H, ~E
  - Flavor Sensitivity for $\pi^{0,+}$, $K^{0,+}$
- Factorization scale 10 GeV^2?

Diffractive channels: HERA results



$$d\sigma \sim e^{B(Q^2)t}$$



[Levy; Frankfurt, Strikman, CW 05]

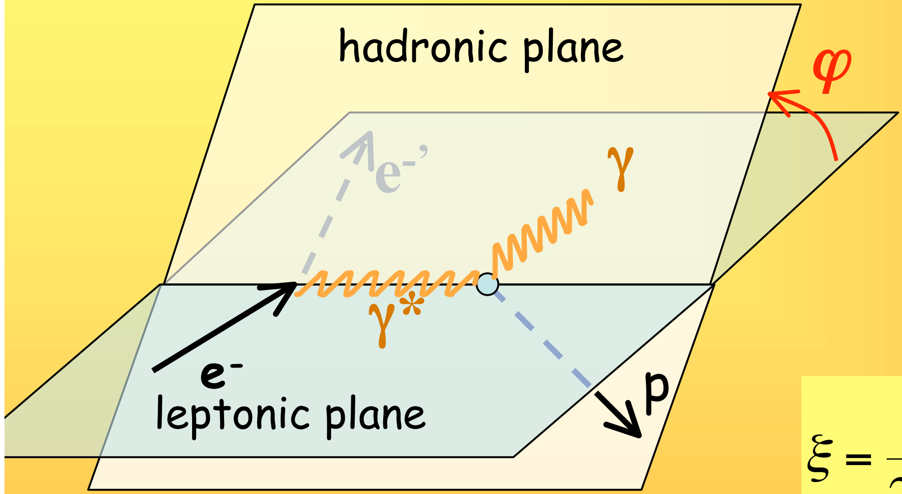
- LO QCD factorization $\leftrightarrow$ Dipole picture
  Gluon GPD $\leftrightarrow$ Color dipole moment

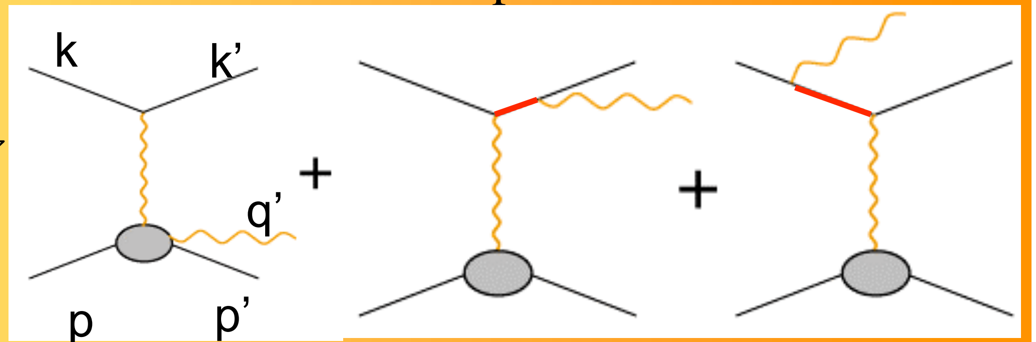
- Measurements of diffractive channels (J/ψ, ϕ, ρ, γ) have confirmed applicability of QCD factorization:
  - Energy dependence changes with Q^2
  - t–slopes universal at high Q^2
  - Flavor relations $\phi : \rho$

- Transverse gluonic size of nucleon
  . . . essential input for small–x physics!

DVCS: The simplest exclusive reaction

- VCS-BH interference gives direct access to the DVCS amplitude.

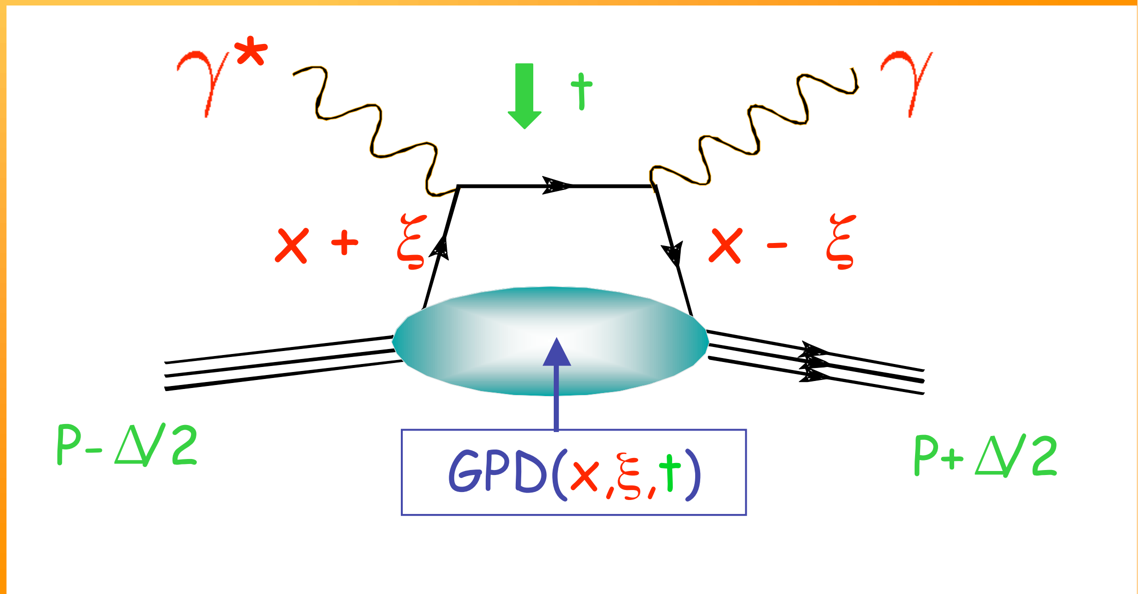




$$\xi = \frac{-\bar{q}^2}{2P\cdot\bar{q}} \rightarrow \frac{x_B}{2-x_B}$$

$$\bar{q} = (q+q')/2$$

- The kinematic dependence of the amplitude on (k, φ, spin), at fixed (ξ, Q^2, t)
- Multiple experimental observables.



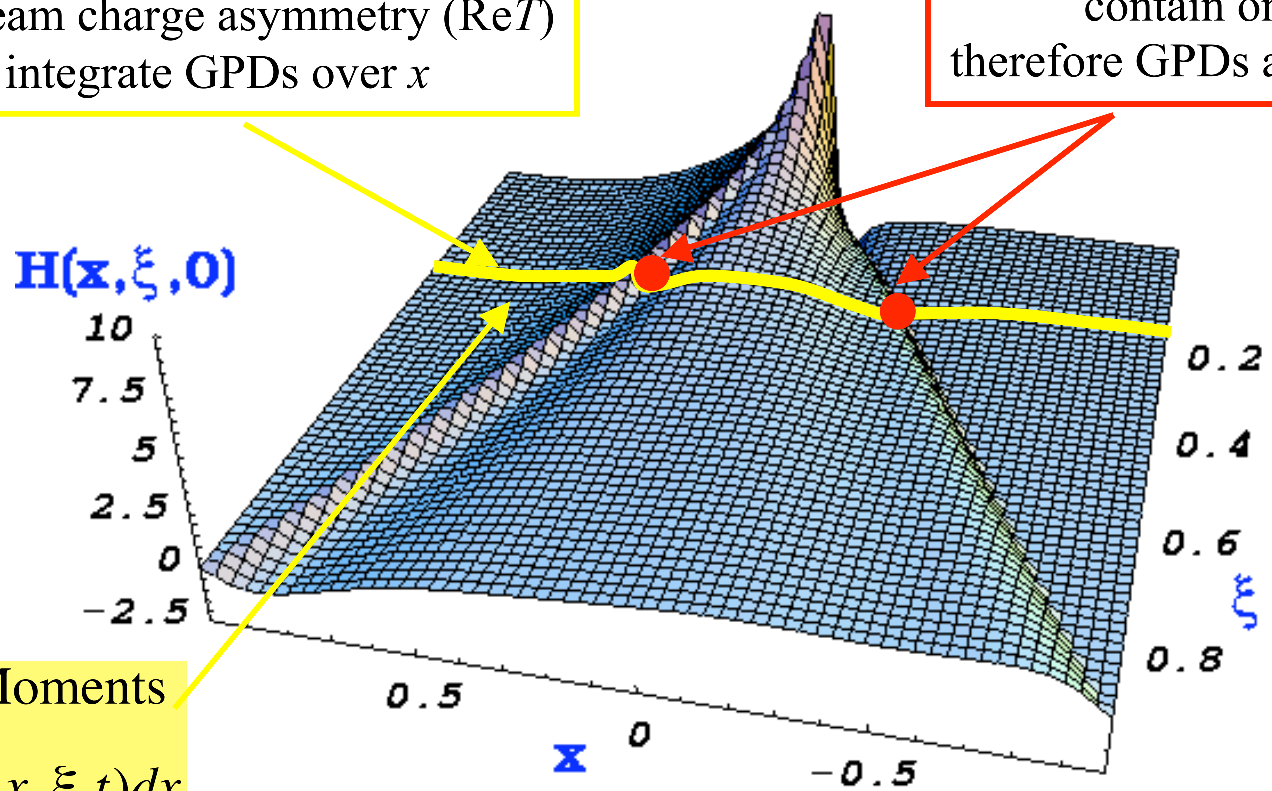
DVCS, GPDs, Compton Form Factors(CFF), and Lattice QCD

(at leading order:)

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

Cross-section (σ) measurement and beam charge asymmetry (ReT) integrate GPDs over x

Beam or target spin $\Delta\sigma$ contain only ImT, therefore GPDs at $x = \xi$ and $-\xi$



Lattice Moments

$= \int x^n H(x,\xi,t) dx$

Twist- & Spin-Structure of Cross Sections

Single Spin Cross Section Differences (~sinϕ):

- Twist-2$\Rightarrow$ $Im[DVCS^{\dagger}BH]$.
- Twist-3$\Rightarrow$ $Im[DVCS^{\dagger}DVCS]$.
- Separable by $s=(k+P)^2$ and Q^2 dependence.

Unpolarized Cross Sections

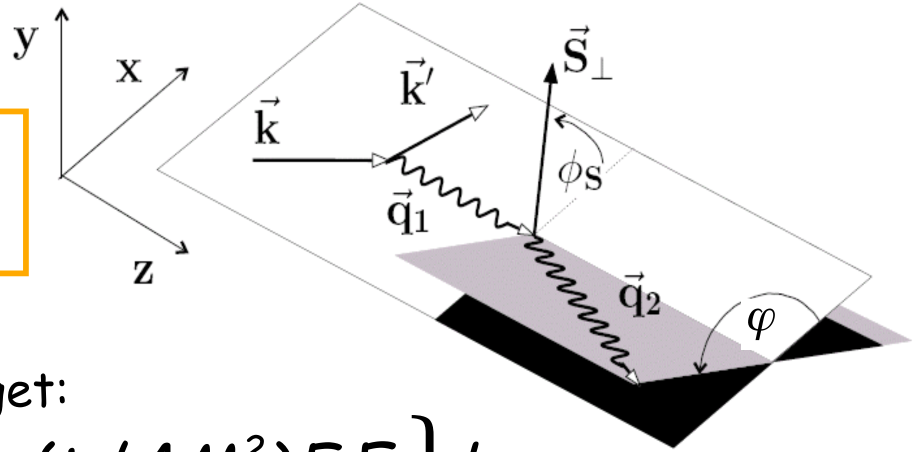
- $d\sigma = |BH|^2 + Re[DVCS^{\dagger}BH] + |DVCS|^2$
  - Only $|BH|^2$ known *a priori*.
  - Twist-2$\Rightarrow$ Re[DVCS†BH] and $|DVCS|^2$ intermingle.
  - Separable with positrons or $s=(k+P)^2$ dependence

Relative Asymmetries

$$A \sim \frac{\mathrm{Im}\left[DVCS^{*}BH\right]}{|BH|^2 + \mathrm{Re}\left[DVCS^{*}BH\right] + |DVCS|^2}$$

- Re, Im parts of Interference and $|DVCS|^2$ all contribute.

Exploiting the harmonic structure of DVCS with polarization



The difference of cross-sections is a key observable to extract GPDs

With polarized beam and unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\varphi \left\{F_1 H + \xi(F_1 + F_2)\tilde{H} + (t/4M^2)F_2 E\right\} d\varphi$$

With unpolarized beam and Long. polarized target:

$$\Delta\sigma_{UL} \sim \sin\varphi \left\{F_1 \tilde{H} + \xi(F_1 + F_2)H + (t/4M^2)F_2 E\right\} d\varphi$$

With unpolarized beam and Transversely polarized target:

$$\Delta\sigma_{UT} \sim \cos\varphi \sin(\phi_S - \varphi)\left\{(t/4M^2)F_2 H - (t/4M^2)F_1 E + \ldots\right\} d\varphi$$

Separations of CFFs $H(\pm\xi,\xi,t)$, $E(\pm\xi,\xi,t)$,…

Steps to Extraction of GPDs from Cross Sections

Single Spin Cross Section Differences measure the Im[Interference Terms]

$$\frac{d^4\vec{\sigma} - d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi} = \frac{\Gamma(x_B, Q^2, t)}{P_1(\varphi)P_2(\varphi)}\left\{s_1^I \sin\varphi + s_2^I \sin 2\varphi\right\}$$

Observable

$$s_1^I = 8Ky(2-y)\,\mathrm{Im}\,C^I(F)$$

$$C^I(F) = F_1\mathrm{H} + \frac{x_B}{2-x_B}(F_1 + F_2)\tilde{\mathrm{H}} - \frac{t}{4M^2}F_2\mathrm{E}$$

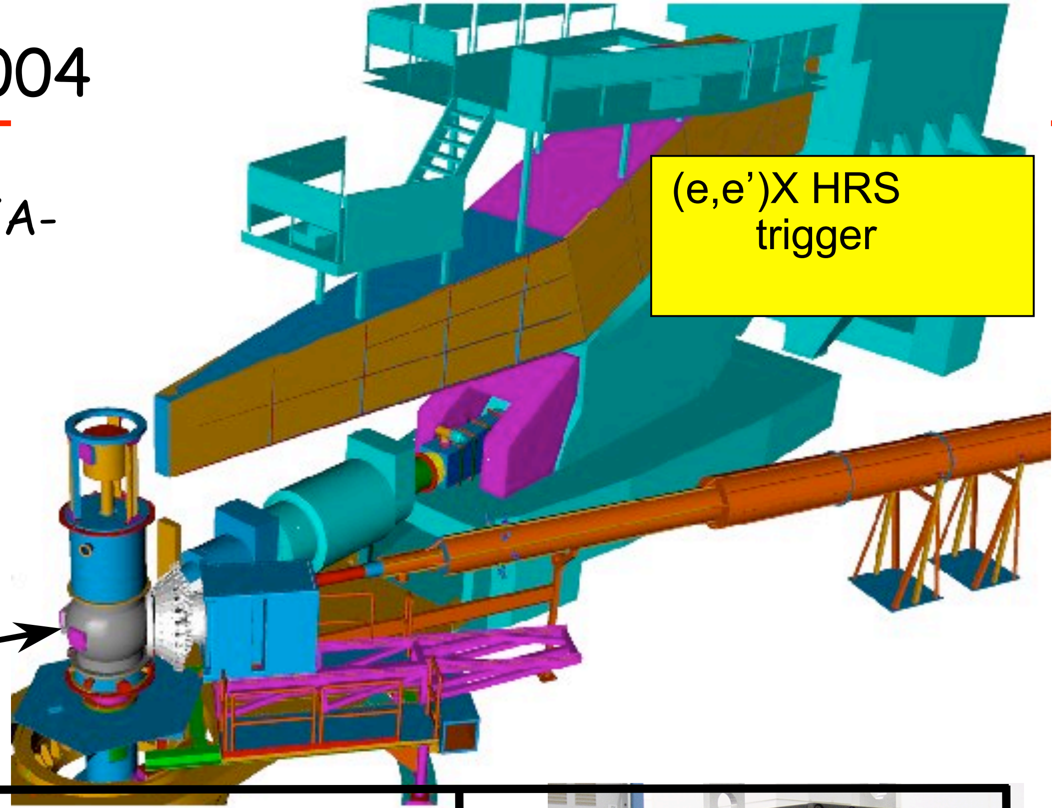
Kinematic factors

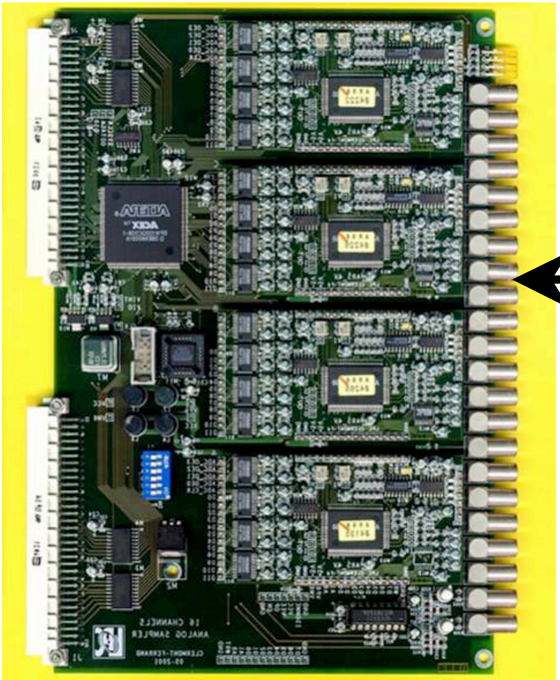
$$\mathrm{Im}\,\mathrm{H} = \pi\sum_q e_q^2\left\{H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right\}$$

GPD !!!

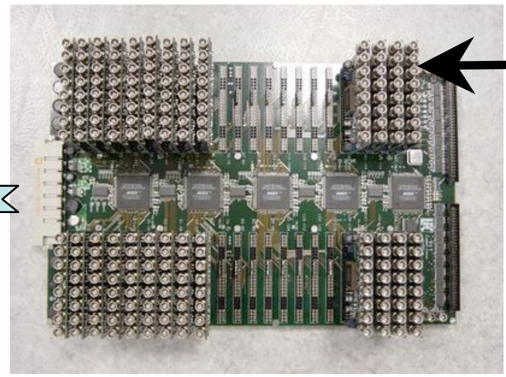
DVCS: Hall A 2004

LPC-Clermont, LPSC-Grenoble, CEA-Saclay, ODU, Rutgers U., JLab

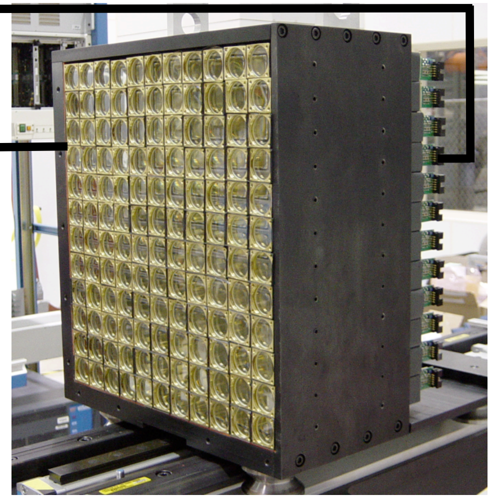




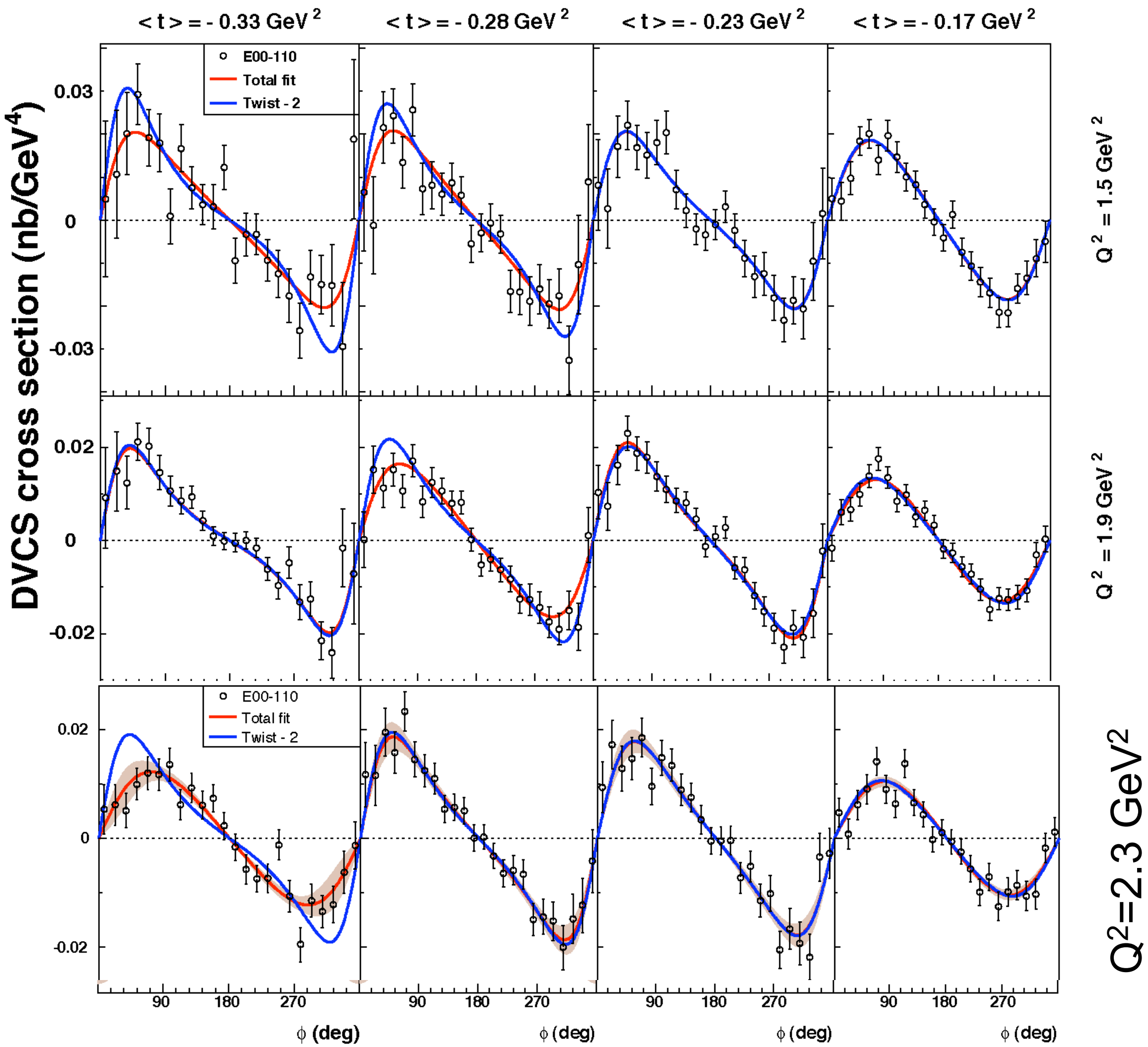
16chan VME6U: ARS
128 samples@1GHz



Digital Trigger Validation



132 PbF_2



Hall A Helicity Dependent Cross sections E00-110 (2004)

PRL**97**:262002 (2006)
C. MUNOZ CAMACHO,
et al.,

Twist-2(GPD)+…

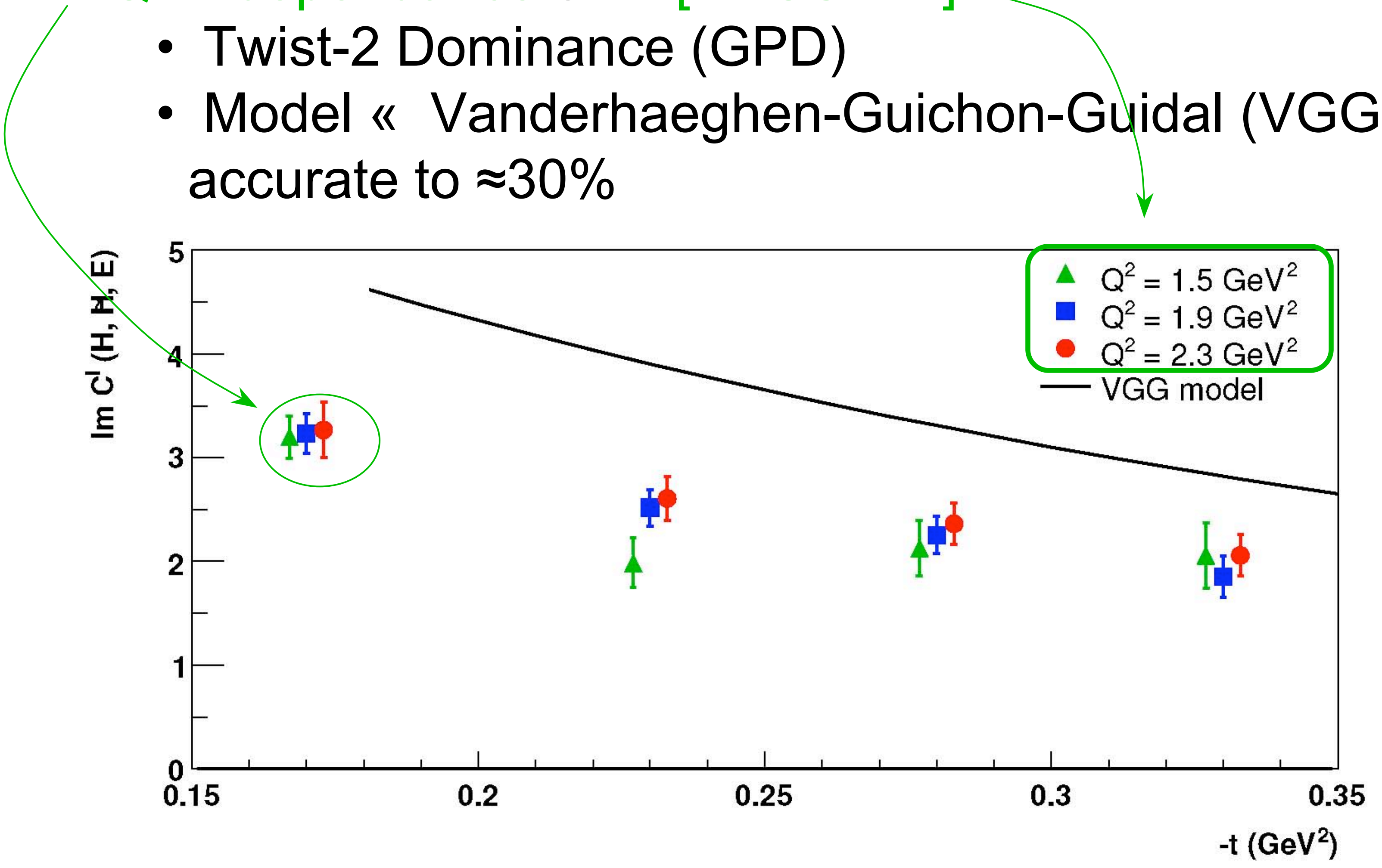
Twist-3(qGq)+…

$$\sum h d\sigma(h) = \frac{s_1 \sin(\phi_{\gamma\gamma})\Gamma_{s1} + s_2 \sin(2\phi_{\gamma\gamma})\Gamma_{s2}}{P_1(\phi_{\gamma\gamma})P_1(\phi_{\gamma\gamma})}$$

$\Gamma_{s1,2}$ = kinematic factors

GPD results from E00-110 (C.MUNOZ CAMACHO et al *PRL* **97**:262002)

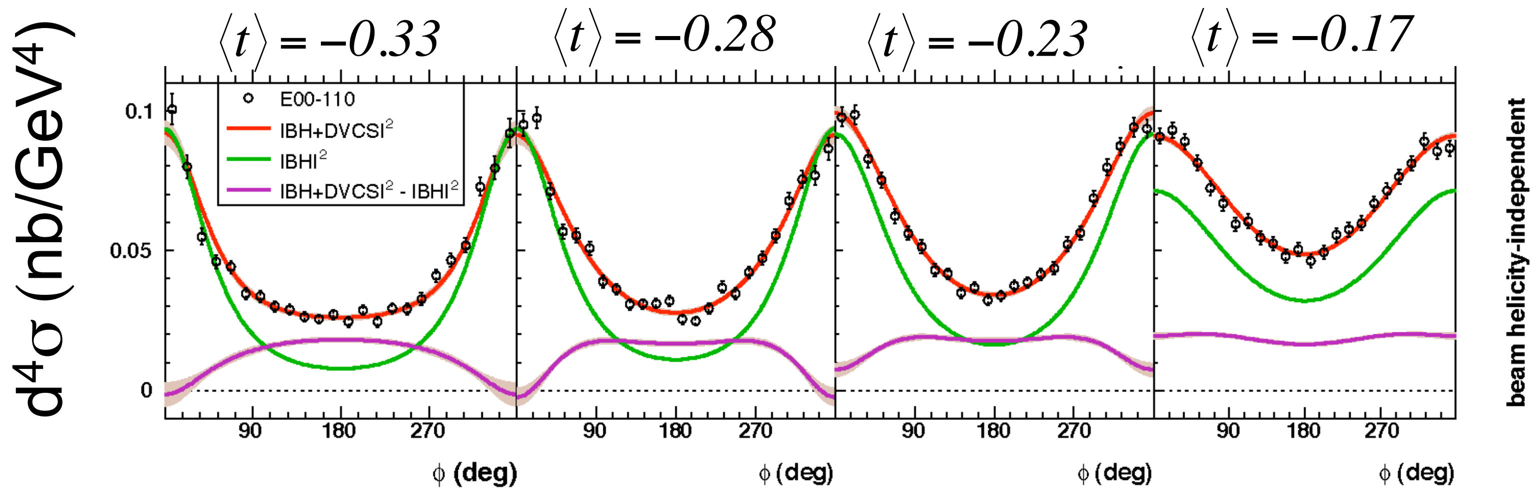
- Q^2-independance of Im[DVCS*BH]
  - Twist-2 Dominance (GPD)
  - Model « Vanderhaeghen-Guichon-Guidal (VGG) » accurate to ≈30%



Beam helicity-independent cross sections at Q^2=2.3 GeV^2, x_B=0.36

- Contribution of Re[DVCS*BH] + |DVCS|^2 large.
- Positron beam or measurements at multiple incident energies to separate these two terms and isolate Twist 2 from Twist-3 contributions

PRL**97**:262002



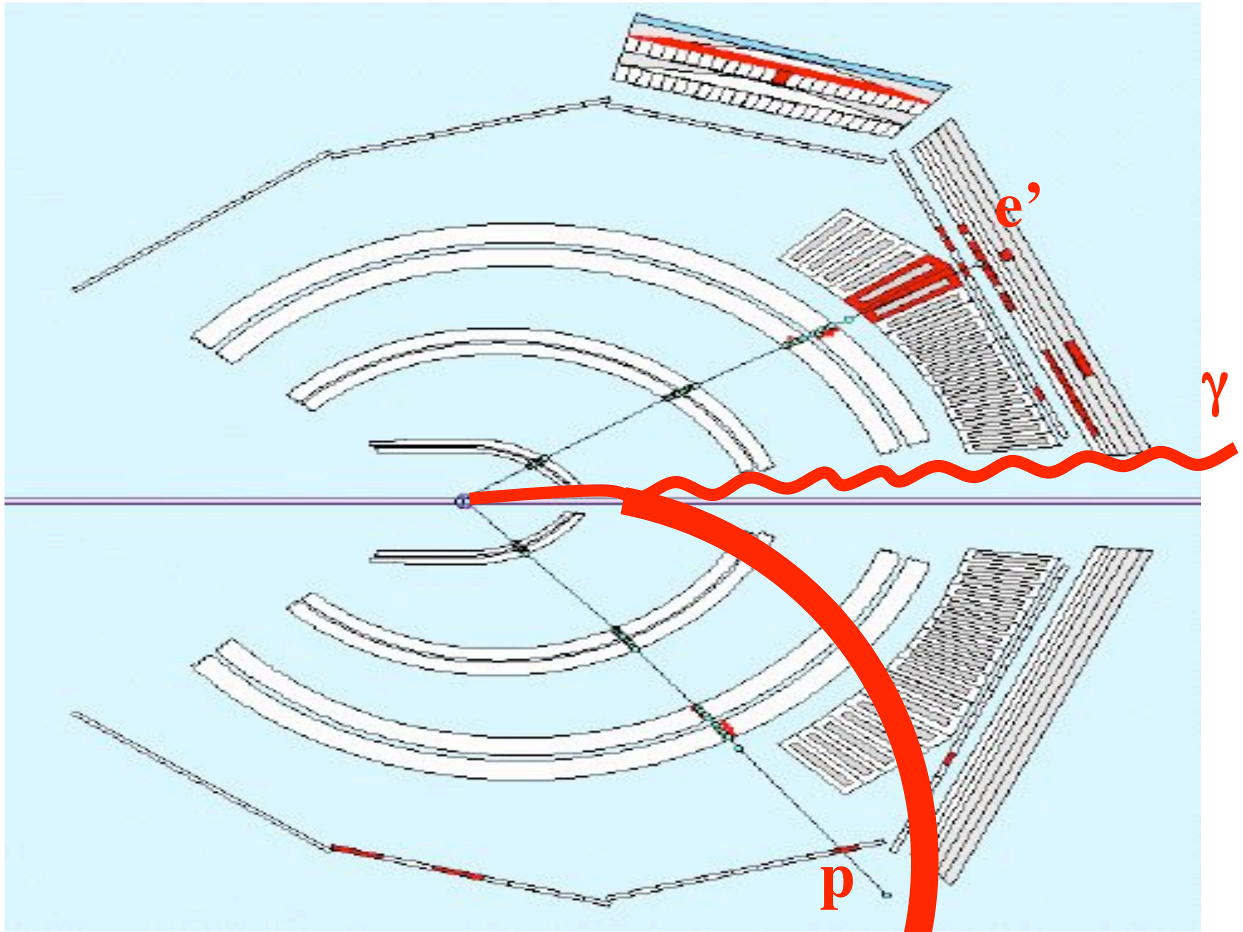
$$d\sigma = d\sigma(|BH|^2) + 2\,\mathrm{Re}[DVCS^* BH] + |DVCS|^2$$

$$= d\sigma(|BH|^2) + \frac{c_0\Gamma_0 + c_1\cos(\phi_{\gamma\gamma})\Gamma_1 + c_2\cos(2\phi_{\gamma\gamma})\Gamma_2 + \ldots}{P_1(\phi_{\gamma\gamma})P_1(\phi_{\gamma\gamma})}$$

$$c_{0,1}(t) \approx \mathrm{Re}[C^I(GPD)] \pm C^{DVCS}\left(GPD^2\right)\ldots + \mathrm{Re}\left[\Delta C^I(GPD)\right]$$

$$c_2(t) = \mathrm{Twist} - 3 = (qGq)$$

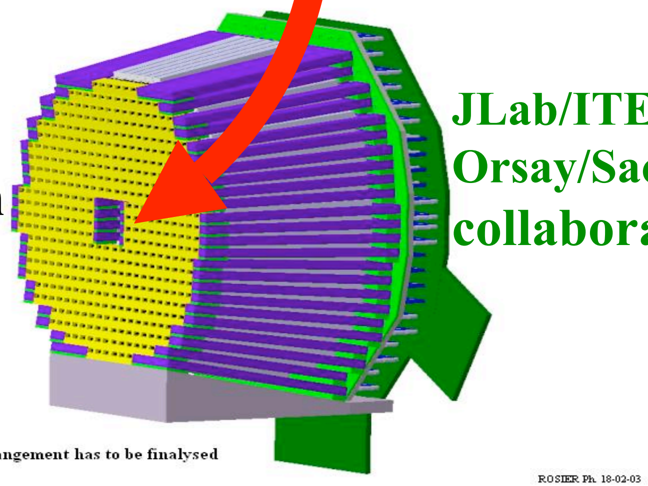
DVCS@Hall B



ep ⇨ epγ

$420\ PbWO_4$ crystals : ~10x10 mm^2, l=160 mm

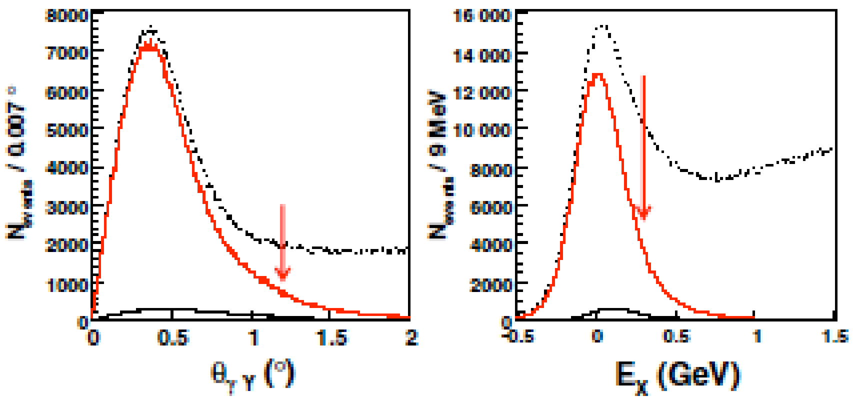
Read-out : APDs +preamps

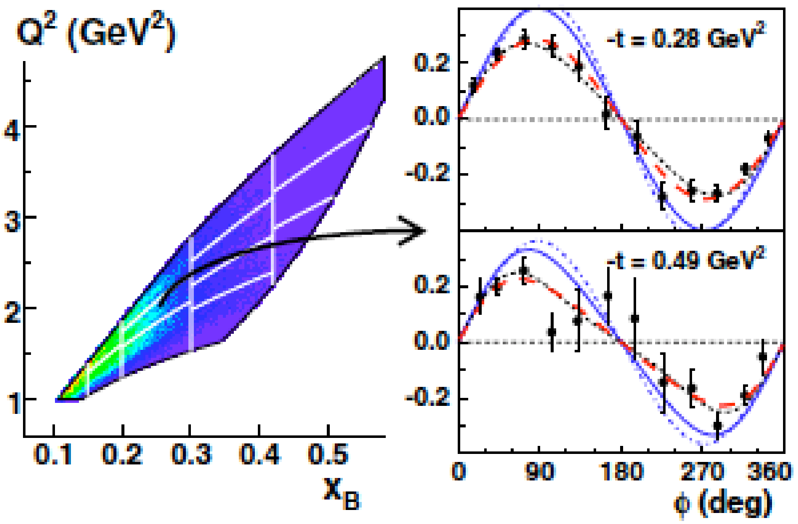


JLab/ITEP/
Orsay/Saclay
collaboration

CLAS 6 GeV
Exclusivity and Kinematics

- H*(e,e'γp)x*
  - Co-linearity of γ with *q-p'*
  - Missing Energy E_X

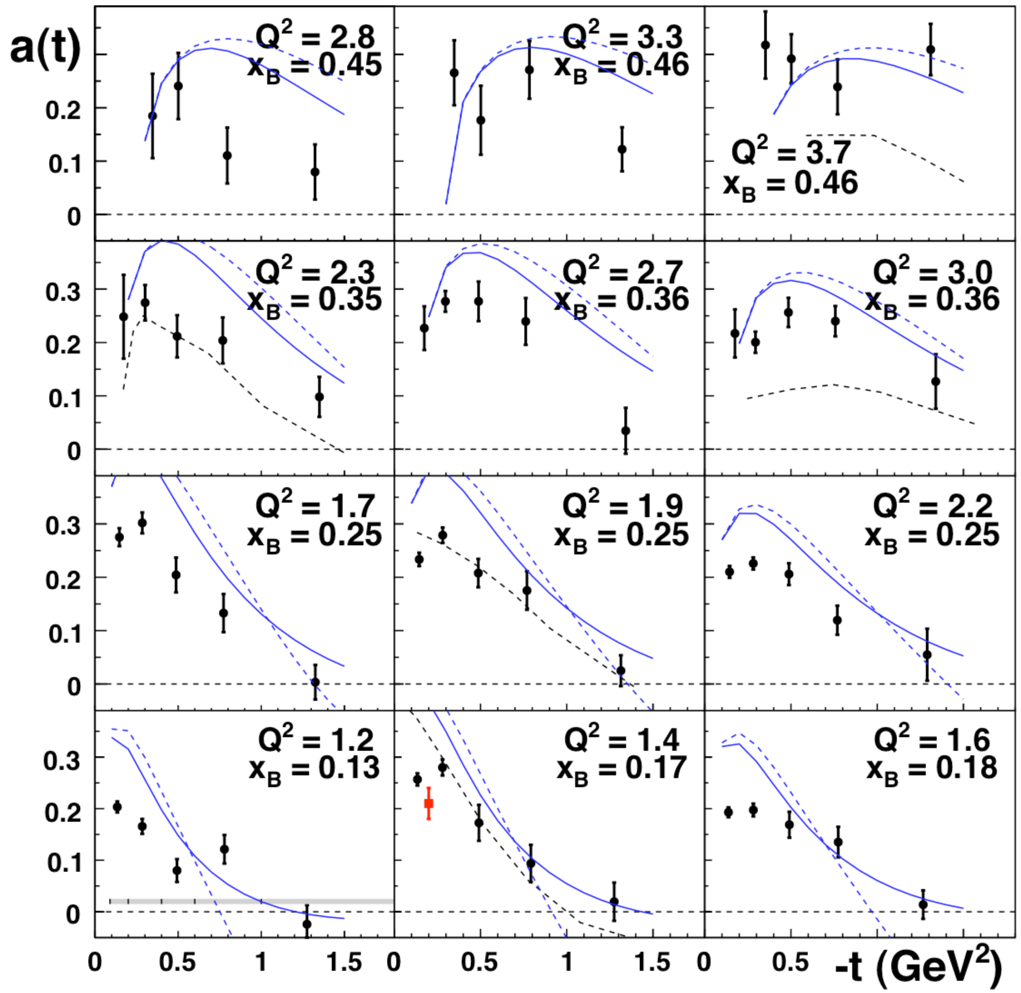




- Example angular distribution of Beam Spin Asymmetry
- One (Q^2, x_B) bin
- Two *t*-bins.

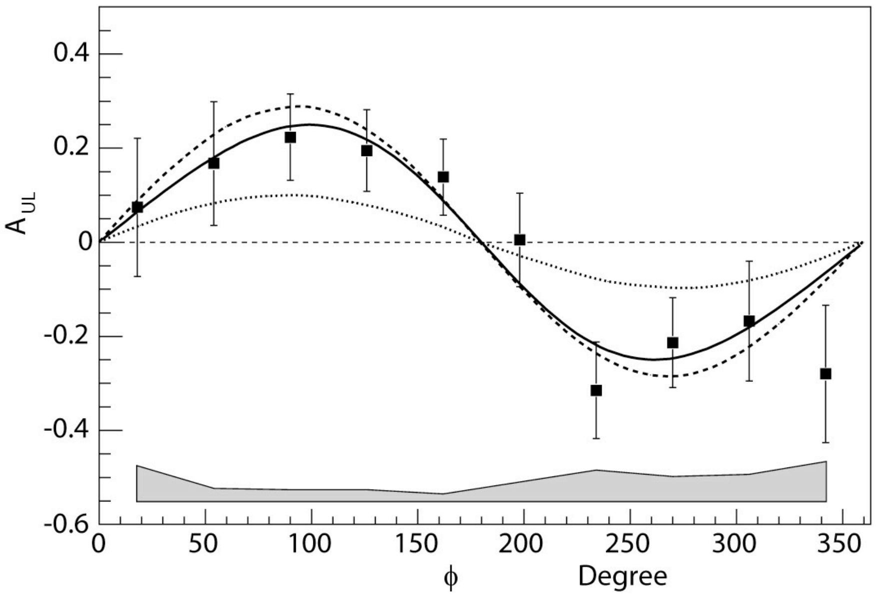
CLAS, 6 GeV Beam Helicity Asymmetry

- Sinϕ moments
- Cross section analysis in progress
- Data set to be doubled by Feb 2009



CLAS: Longitudinally Polarized Protons A_{UL}

JLab/Hall B - Eg1
Non-dedicated experiment, but
H(e,e'γp) fully exclusive)



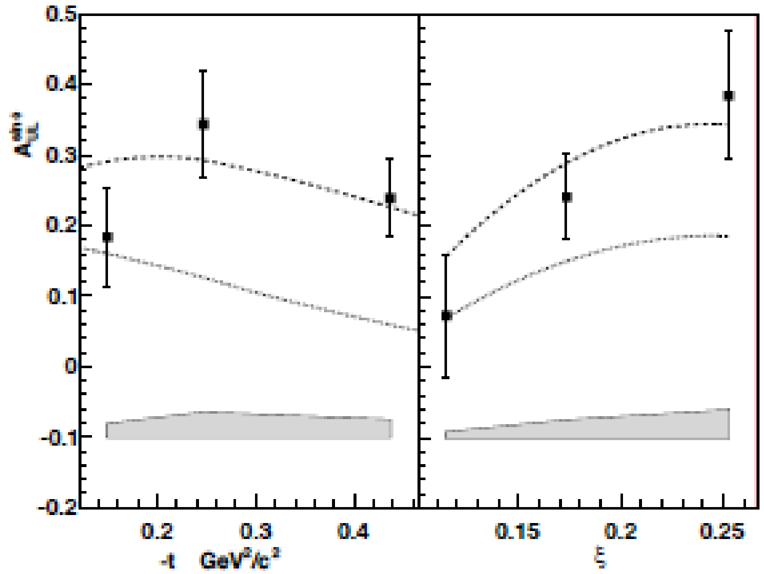


FIG. 6: The left panel shows the $-t$ dependence of the $\sin\phi$-moment of A_{UL} for exclusive electroproduction of photons, while the right shows the ξ dependence. Curves as in Fig. 5.

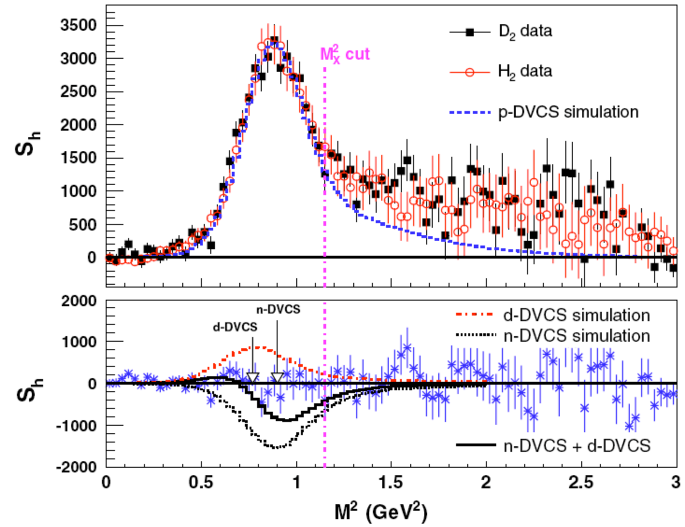
S.Chen, *et al*, PRL 97, 072002 (2006)

Higher statistics run coming in 2009
…on to 12 GeV

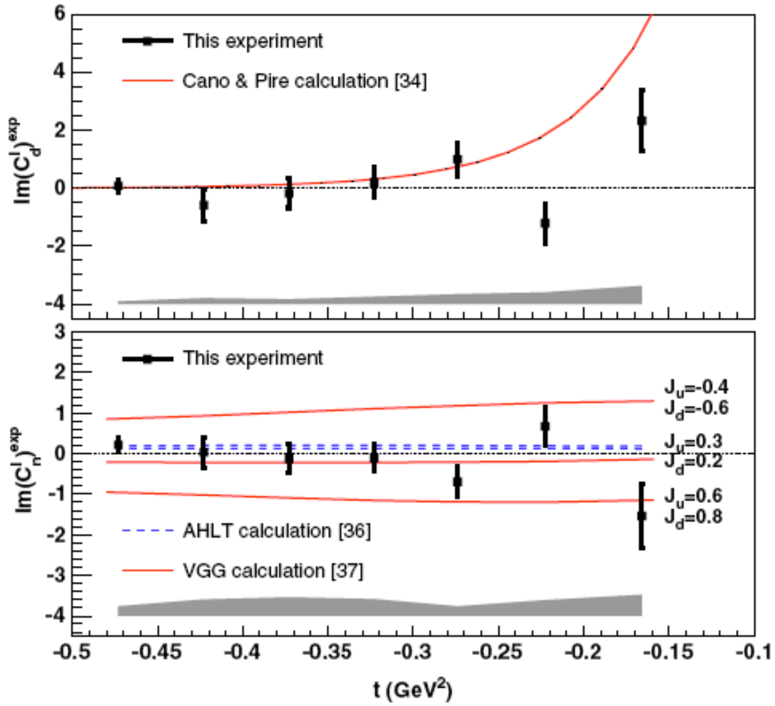
DVCS-Deuteron, Hall Q

- E06-007:
  - D(e,e'γ)X ≈ *d(e,e'γ)d+n(e,e'γ)n+p(e,e'γ)p*
  - Sensitivity to *$E_n(\xi,\xi,t)$ in Im[DVCS*BH]*
  - Sensitive to *$(4J_d+J_u)/9$*

- E08-025 (6 GeV- 2010)
  - Reduce the systematic errors
  - Separate the *Re[DVCS*BH]* et *|DVCS|*^{2} terms on the neutron via two beam energies.



Q^2=2.3 GeV^2, x_B=0.36



Progress Towards the Ji Sum-Rule of the Nucleon Spin ⇒ L_q.

Single parameter fits to model of GPD(x,ξ) at **one** point $x = \xi = x_{Bj}/(2- x_{Bj})$ for a single value of x_{Bj}.

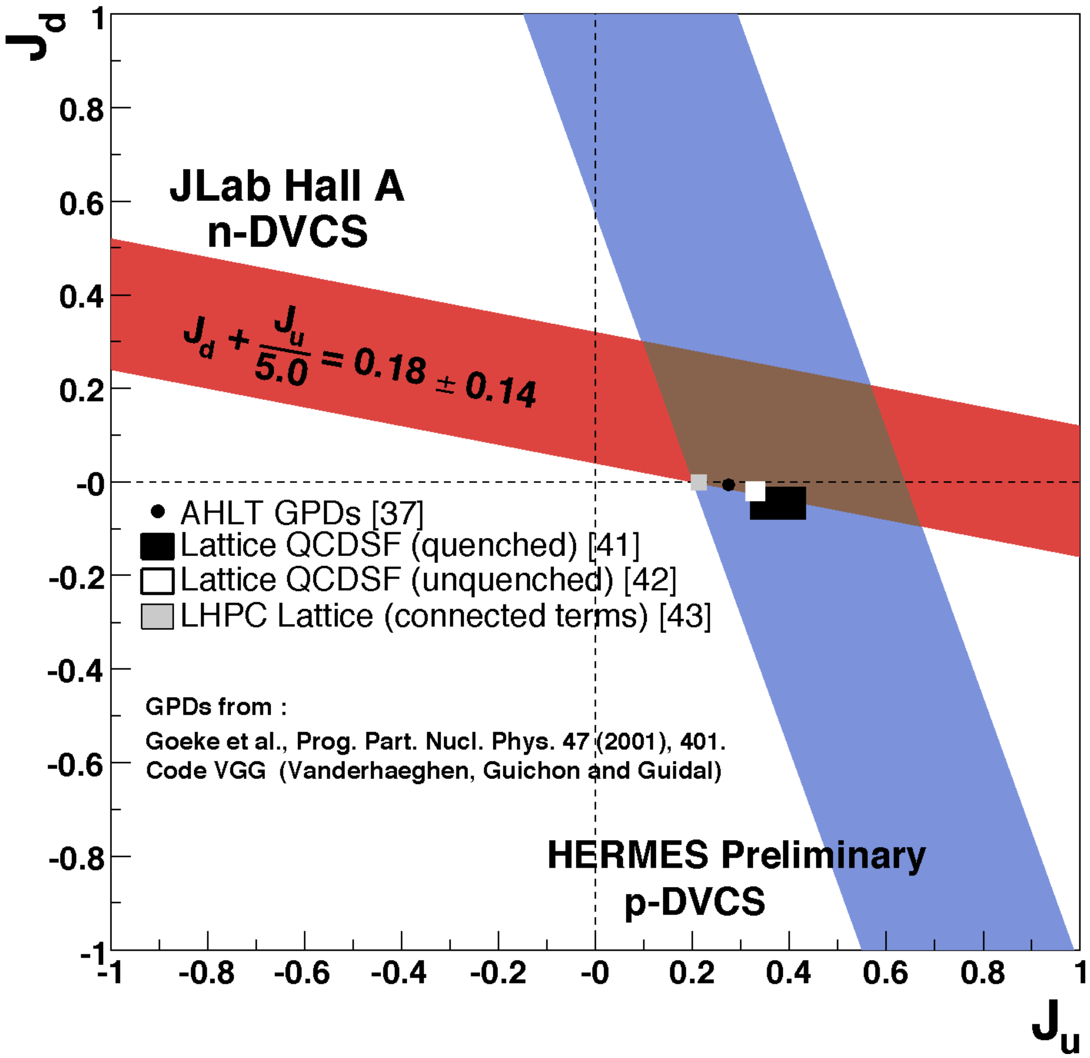
Illustrative of future results with more extensive measurements.

HERMES: E_{proton} from transversely polarized target

Hall A: $E_{neutron}$ from helicity dependent cross section *D(e,e'γ)pn.*

Malek MAZOUZ, et al.,

Phys.Rev.Lett. **99**:242501, 2007



12 GeV DVCS program

- Proton DVCS
  - Beam spin dependent cross sections and asymmetries
  - Longitudinal target spin observables
  - Work in progress for transverse target spin observables
    - HD target, electron beam tests in 2010.
- Neutron DVCS
  - Quasi Free in Deuterium
    - Mixing of D and n, bound nucleon effects
    - Feasibility studies for n-tagging in CLAS12, and d-tagging in Hall A and CLAS12.
  - Feasibility studies of longitudinal and transverse spin observables in polarized ^{3}He (Hall A)
- Nuclear DVCS
  - Deuteron
  - $^{4}He(e,e'\gamma\alpha)$ in BoNuS detector (CLAS) 2009-2010

Personal estimate of DVCS Status 2018

- Precision tests of factorization with Q^2 range ≥ 2:1 for
  - $x_B \in [0.25,0.6]$. t_{min}-t < 1 GeV^2.
  - Proton unpolarized target observables
  - Im[DVCS*BH], Re [DVCS*BH], $|DVCS|^2$.
- Longitudinal, transverse target spin observables
  - Separations of H, E,~H,~E at $x = \pm\xi = \pm x_B/(2-x_B)$ point.
- Partial *u,d* flavor separations from quasi-free neutron.
- Coherent Nuclear DVCS on D, He
- COMPASS data: $x_B \in [0.01,0.1]$
- Final, fully exclusive, HERMES run

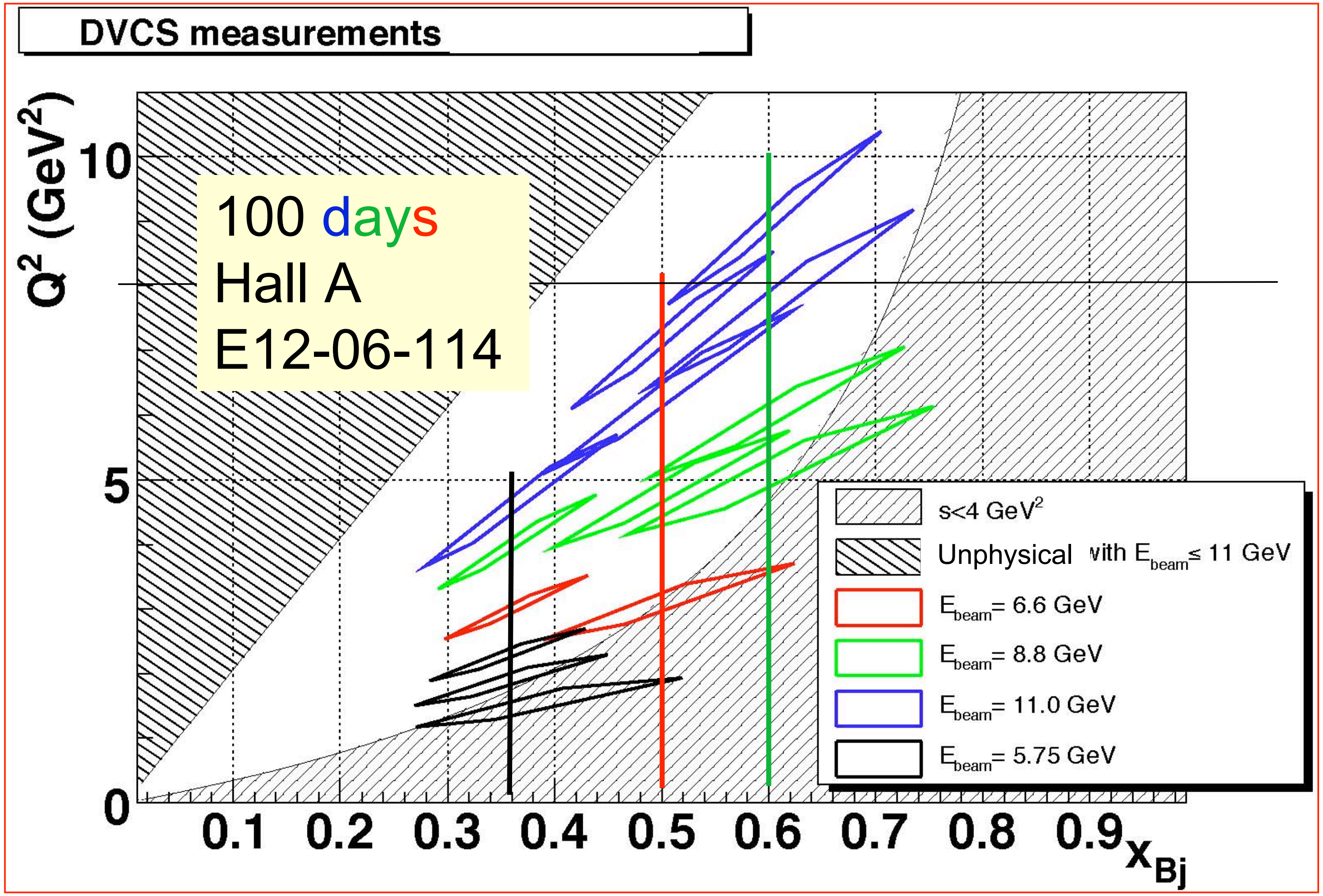
•Spatial imaging possible at $x=\xi$ (M. Burkardt)

•Strong constraints on full GPD(x,ξ,t) from experiment and lattice

•Need additional phenomenology to determine model dependence of full GPDs, sum rules

JLab12: 3, 4, 5 pass beam

Hall A: Absolute Cross Section measurements: $d\sigma(h_e=\pm1)$



- Large Q^2 range at each x_B.
- x_B = 0.36, 0.5, 0.6

HD ice : a transversely polarized target for CLAS

Operates at **T~500-750mK**
•Long spin relaxation times (months)
•Weak transverse magnetic field

- 25+ years of development…
- Successful operation at LEGS photon beam
- Just in time for DVCS!!!!

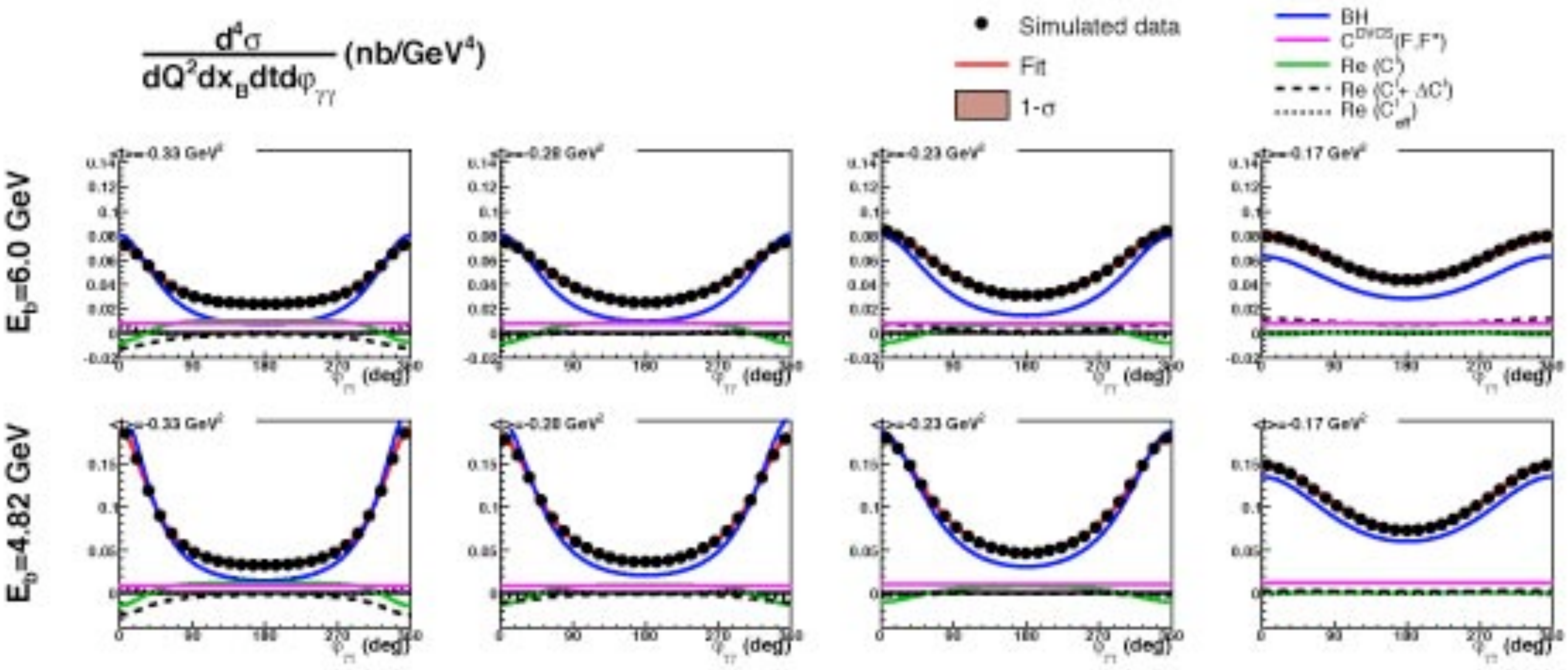
Material	gm/cm^2	mass fraction
HD	0.735	77%
Al	0.155	16%
CTFE (C_2ClF_3)	0.065	7 %

Test in 2010 with electron beam, Experiment conditionally scheduled in 2011

Heat extraction is accomplished with thin aluminum wires running through the target

E07-007 Q^2=1.5, 1.9, 2.3 GeV^2, x_B=0.36 (2010)

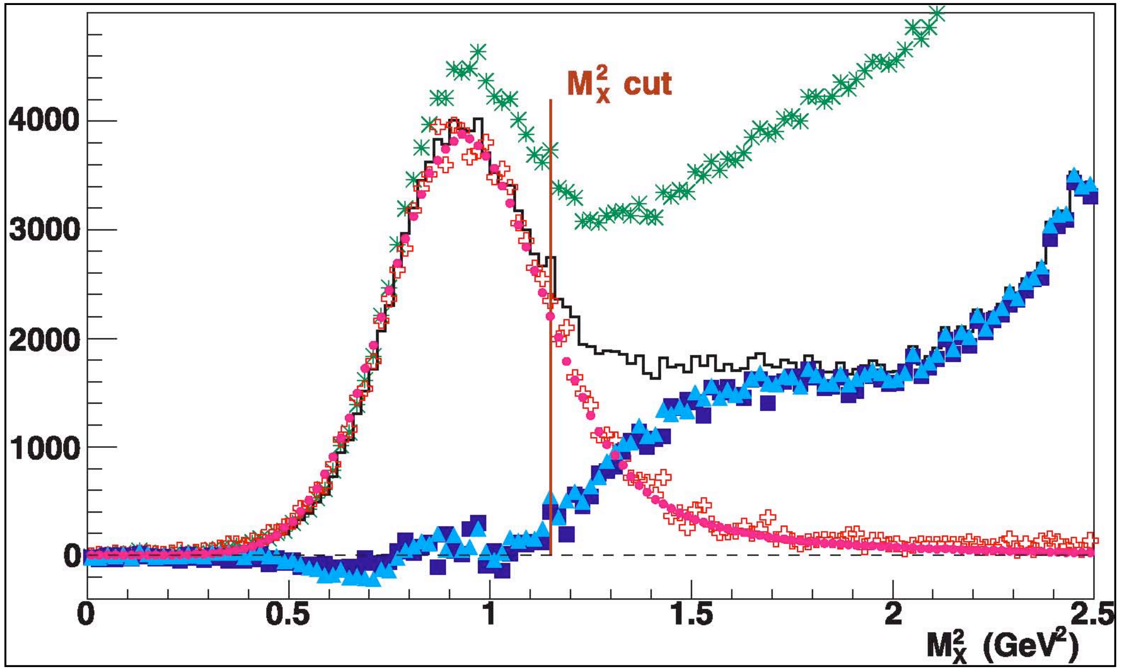
Measure DVCS cross sections at two beam energies
Expand Calorimeter for improved π^0 subtraction
Separate Re[DVCS*BH] from |DVCS|^2.



E07-007 Simulation Q^2=2.3 GeV^2

$$d\sigma = d\sigma(|BH|^2) + 2\,\mathrm{Re}[DVCS^*BH] + |DVCS|^2$$

DVCS Exclusivity in Hall A



- Cross section analysis based on H(e,e'γ)X data
- Exclusivity confirmed by sample of H(e,e'γp) events